SIR Analysis of Overloaded CDMA System Using Orthogonal Gold Codes

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***Abstract*— This paper introduces a direct-sequence code-division multiple access (DS/CDMA) concept which accommodates a higher number of users than the spreading factor N. This new multiple access concept makes use of two sets of orthogonal signal waveforms, one for the first set of users and the other for the additional users. The two sets of users are scrambled by a set specific pseudonoise sequence. A two stage and three stage conventional and weighted parallel detection technique is proposed to cancel interference between the two sets of users. The signal to interference ratio of the two sets of users is derived. The proposed technique thus accommodates N users without any mutual interference and a number of additional users at the expense of a small signal-to-noise ratio penalty.**

***Index Terms*— Gold codes, Linear Parallel Interference Cancellation (LPIC), Multiple Access (MA), Multiple Access Interference (MAI), Overloading, Signal to Interference(SIR) Ratio.**

I. Introduction

Multiple access (MA) communication represents an active area of current research since it is the only means of communication among users in wireless systems such as mobile and cellular terrestrial systems and satellite based systems. One of the category of multiple access technique is orthogonal-waveform multiple access (OWMA), which includes FDMA, TDMA, OFDMA, CDMA with orthogonal spreading sequences (called orthogonal CDMA, or OCDMA), and any other multiple access technique which assigns orthogonal signal waveforms. The other category includes direct-sequence CDMA and frequency-hopping CDMA with pseudo-noise (PN) spreading sequences. This paper concentrates on direct-sequence CDMA with PN sequences which is referred as PN-CDMA. The beauty of the multiple access concept presented in [6] is that it combines the advantages of OWMA and PN-CDMA while avoiding their shortcomings and undesirable features.

A DS/CDMA scheme which can accommodate N users without any mutual interference, while also accommodating a number of additional users at the expense of some SNR penalty is devised. The proposed technique consists of assigning one set of orthogonal gold codes to the first N users, and another set of orthogonal gold codes to the additional users, but overlaying them with a different PN sequence, for all additional users. The signals transmitted by users from the same set are mutually orthogonal, but there is no orthogonality between users from different sets. Detection is performed iteratively, each iteration consisting of two steps, one to detect the signals transmitted by the first set of users and the other to detect the signals transmitted by the second set of users. The introduction of orthogonal/orthogonal gold codes is justified by the fact that the set-1 users suffer from interference of the set-2 users only, while the set-2 users suffer from interference of the set-1 users only resulting in residual multiple-access interference present at the filter output.

One approach to tackle multiuser interference problem is to employ a suitable linear transformation on the matched filter outputs. Belonging to this family is the so-called decorrelating receiver [10]. Another popular approach is to employ interference cancellation, i.e., to attempt removal of the multiuser interference from each user's received signal before making data decisions. In principle, the IC schemes considered in the literature fall into two categories, namely, successive and parallel cancellation. The advantage is that they do not require significant complexity when compared to minimum mean square error-MMSE detector [11], decorrelating detector [10] or linear decision directed interference cancellation [12]. The first PIC detector for code division multiple access (CDMA) communication systems was derived by Varanasi and Aazhang in [8] where their PIC detector was called a multistage detector. The multistage detector was shown to have close connections to the optimum maximum-likelihood detector and also to possess several desirable properties. In [5] the MAI estimates are weighted before cancellation and the value of the weights are low at the early stages and large at the later stages. An iterative linear parallel interference cancellation [3] technique is adopted to cancel interference in unscrambled DS/CDMA system for N users.

P. Kumar et al. [1] have studied the overloading performance of Orthogonal / Scrambled Orthogonal (O/S-O), which is a modification of S-O/O scheme. In S-O/O scheme the same set of Walsh- Hadamard sequence is scrambled by a set specific pseudo-random (PN) sequence. A method of accommodating K=N+M users in an N-dimensional signal space that does not compromise the minimum Euclidean distance of the orthogonal signaling has been presented in [9] for AWGN channel. A tree-like correlation coefficient structure of user signatures suitable for optimal multiuser detection has been proposed in [7]. A new overloading scheme using hybrid techniques has been proposed in [2], where the spreading codes and transmission modes are different for the two sets to

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increase the overloading performance. The example developed by H. Sari, F. Vanhaverbeke, and M. Moeneclaey [4] is based on a particular combination of TDMA and OCDMA.

A multistage Conventional Linear Parallel Interference Cancellation (CLPIC) and Weighted Linear Parallel Interference Cancellation (WLPIC) is adopted in this paper to cancel the interference. In parallel interference cancellation each stage uses the prior stage's tentative decision outputs to generate new multiple-access interference estimates. These interference estimates are subtracted from the original observation to produce new tentative decision outputs with presumably lower multiple-access interference.

This paper is organized as follows. In the next section, basic principle is described. Interference cancellation is presented in section-3 and SIR analysis in section-4. Section-5 explains about the Simulation results. Finally, conclusion of this paper is presented.

II. Basic Principle

Consider a DS/CDMA system with a spreading factor of N, and assume that K=N+M, (where M<N) number of users is to be accommodated. The following notation for the discrete-time matrix model of the received BPSK modulated CDMA signal after demodulating and chip matched filtering will be used.

$$y = b_1A_1h_1S_1 + b_2A_2h_2S_2 + n \quad (1)$$

Let us denote S_1 and S_2 as the signature matrices of the set-1 and set-2 users respectively. The signature waveform may be expressed as

$$s_{u,k_u}(t) = \sum_{j=1}^{N} s^{j}_{u,k_u} p_c(t - jT_c) \quad (2)$$

where $s^{j}_{u,k_u} \in \{1, 1\}$, Tc is the chip duration and $p_c(t)$ is the real valued unit-energy rectangular chip pulse. In this paper, two different orthogonal Gold code sets for set-1 and set-2 users are considered. Let us denote b_1 and b_2 as the data matrices of the set-1 and set-2 users respectively. The data signal $b_{u,k_u}(t)$ of the k[th] users in set-u, may be expressed as

$$b_{u,k_u}(t) = \sum_{l=-\infty}^{\infty} b^{l}_{u,k_u} p_{T_b}(t - lT_b) \quad (3)$$

where the data sequences $b^{l}_{u,k_u} \in \{-1,1\}$ are independent and identically distributed (i.i.d.) random variables taking values of +1 and -1 with equal probability. In eqn.[3] T_b is the bit duration, N is the spreading factor and $p_{T_b}(t)$ is the rectangular pulse of the information data bits. Matrices A_1 and A_2 are diagonal matrices of received signal amplitudes for two sets of users and can be expressed as

$$A_1 = \mathrm{diag}[A_{1,1}\cos(\phi_{1,1}),\ldots, A_{1,N}\cos(\phi_{1,N})] \quad (4)$$

$$A_2 = \mathrm{diag}[A_{2,1}\cos(\phi_{2,1}),\ldots, A_{2,M}\cos(\phi_{2,M})] \quad (5)$$

In eqn.(4,5), A_{u,k_u} is the complex channel attenuation for the k[th] user of the set-u. For AWGN channel, $A_{u,k_u}=1$. The phase term is ϕ_{u,k_u} for the k[th] user in set-u. The orthogonal Gold codes of both the sets are overlaid by a set-specific pseudo-noise (PN) sequence which is the same for all users within the set. In order to split the interference power evenly over the in-phase and quadrature components of the useful signal (irrespective of the carrier phase), we consider complex valued PN sequences: the chips p_{nu} randomly takes their values from the set $\{\exp(j\pi/4), \exp(j3\pi/4), \exp(j5\pi/4), \exp(j7\pi/4)\}$.

III. Interference Cancellation

We consider a multistage conventional and weighted LPIC at the receiver. The first stage is a conventional matched filter (MF), which is a bank of K correlators, each matched to a different user's spreading waveform. The received vector $y^{(1)}_{k_1}$ and $y^{(1)}_{k_2}$ at the output of the first stage of the matched filter detector for the set-1 users and set-2 users (the superscript (1) in $y^{(1)}_{k_1}$ denotes the first stage) respectively are given by

$$y^{(1)}_{k_1} = A_{k_1} h_{k_1} b_{k_1} + \sum_{k_2=1}^{M} \rho_{k_1k_2} A_{k_2} h_{k_2} b_{k_2} + n_{k_1} \quad (6)$$

$$y^{(1)}_{k_2} = A_{k_2} h_{k_2} b_{k_2} + \sum_{k_1=1}^{N} \rho_{k_1k_2} A_{k_1} h_{k_1} b_{k_1} + n_{k_2} \quad (7)$$

where $\rho_{k_1k_2}$ is the cross-correlation coefficient between the set-1 users and set-2 users spreading waveforms, given by $\rho_{k_1k_2} = \int_0^T s_{k_1}(t)s_{k_2}(t)dt$, $|\rho_{k_1k_2}| \le 1$, and n_k's are complex Gaussian with zero mean and variance equal to σ_2. The received vector $y^{(1)}_{k_1}, y^{(1)}_{k_2}$ is used for multiaccess interference(MAI) estimation and cancellation in the second stage of parallel interference cancellation.

A. Conventional LPIC

In LPIC, the MAI estimate for the set-1 users in stage m, m > 1, is obtained by multiplying $y^{(m-1)}_{k_2}$ with $\rho_{k_1k_2}$ and summing them up. More specifically, an estimate of the MAI for a desired user in the current stage is obtained using all the other user's soft outputs from the previous stage for cancellation in the current stage. Accordingly, the bit decision for the set-1 users after interference cancellation in the m[th] stage is given by

$$b^{(m)}_{k_1} = \mathrm{sgn}\left(\mathrm{Re}\left(h^{*}_{k_1}\left(y^{(1)}_{k_1} - \sum_{k_2=1}^{M} \rho_{k_1,k_2} y^{(m-1)}_{k_2}\right)\right)\right) \quad (8)$$

Similarly, the bit decision for the set-2 users after interference cancellation in the m[th] stage is given by

$$b^{(m)}_{k2} = \mathrm{sgn}\left(\mathrm{Re}\left(h^{*}_{k_2}\left(y^{(1)}_{k_2} - \sum_{k_1=1}^{N} \rho_{k_1,k_2} y^{(m-1)}_{k_1}\right)\right)\right) \quad (9)$$

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B. Weighted LPIC

In a weighted LPIC, the MAI estimate for the set-1 users and set-2 users in stage m, m > 1, is weighted by a factor $p_{k_1}^{(m)}$ and $p_{k_2}^{(m)}$ respectively before cancellation. The m[th] stage output of the set-1 users and set-2 users respectively are given by

$$y_{k_1}^{(m)} = y_{k_1}^{(1)} - p_{k_1}^{(m)} \sum_{k_2=1}^{M} \rho_{k_1,k_2}\, y_{k_2}^{(m-1)} \qquad (10)$$

$$y_{k_2}^{(m)} = y_{k_2}^{(1)} - p_{k_2}^{(m)} \sum_{k_1=1}^{N} \rho_{k_1,k_2}\, y_{k_1}^{(m-1)} \qquad (11)$$

The bit decision for the set-1 users and set-2 users after weighted interference cancellation in stage m is

$$b_{k_1}^{(m)} = \mathrm{sgn}\left(\mathrm{Re}\left(h_{k_1}^{*}\, y_{k_1}^{m}\right)\right) \qquad (12)$$

$$b_{k_2}^{(m)} = \mathrm{sgn}\left(\mathrm{Re}\left(h_{k_2}^{*}\, y_{k_2}^{m}\right)\right) \qquad (13)$$

In the following, we obtain exact expressions for the average SIR's at the output of the weighted LPIC.

IV. SIR Analysis

A.. Average SIR at 2nd Stage Output

The weighted interference cancelled output of the 2nd stage for the set-1 users is given by

$$y_{k_1}^{(2)} = y_{k_1}^{(1)} - p_{k_1}^{(1)} \sum_{k_2=1}^{M} \rho_{k_1,k_2}\, y_{k_2}^{(1)}$$

$$= A_{k_1} h_{k_1} b_{k_1} \left(1 - p_{k_1}^{(2)} \sum_{k_2=1}^{M} \rho_{k_1,k_2}^{2}\right) + I_{k_1}^{(2)} + N_{k_1}^{(2)} \qquad (14)$$

The terms $I_{k_1}^{(2)}$ and $N_{k_1}^{(2)}$ in (14) represent the interference and noise terms introduced due to imperfect cancellation in using the soft output values from the matched filter stage. Since h_k's are complex Gaussian, both $I_{k_1}^{(2)}$ and $N_{k_1}^{(2)}$ are linear combinations of Gaussian random variable with zero mean and variance equal to $\sigma^2_{I_{k_1}^{(2)}}$ and $\sigma^2_{N_{k_1}^{(2)}}$ respectively.

The average SIR of the set-1 users at the output of the second stage, $SIR_{k_1}^{(2)}$ is then given by

$$SIR_{k_1}^{(2)} = \frac{2A_{k_1}^{2}\left(1 - p_{k_1}^{(2)} \sum_{k_2=1}^{M} \rho_{k_1,k_2}^{2}\right)^{2}}{\sigma^2_{I_{k_1}^{(2)}} + \sigma^2_{N_{k_1}^{(2)}}} \qquad (15)$$

Similarly, the average SIR of the set-2 users at the output of the second stage, $SIR_{k_2}^{(2)}$ is then given by

$$SIR_{k_2}^{(2)} = \frac{2A_{k_2}^{2}\left(1 - p_{k_2}^{(2)} \sum_{k_1=1}^{N} \rho_{k_1,k_2}^{2}\right)^{2}}{\sigma^2_{I_{k_2}^{(2)}} + \sigma^2_{N_{k_2}^{(2)}}} \qquad (16)$$

B. Average SIR at 3rd Stage Output

The soft values of the interference cancelled outputs of all the other users from the second stage are used to reconstruct (estimate) the MAI for the set-1 user in the third stage. The MAI estimate is then weighted by the factor $p_{k_1}^{(3)}$ and cancelled. The third stage output of the set-1 user, $y_{k_1}^{(3)}$ is then given by

$$y_{k_1}^{(3)} = y_{k_1}^{(1)} - p_{k_1}^{(3)} \sum_{k_2=1}^{M} \rho_{k_1,k_2}\, y_{k_2}^{(2)}$$

$$= A_{k_1} h_{k_1} b_{k_1} X + I_{k_1}^{(3)} + N_{k_1}^{(3)} \qquad (17)$$

where

$$X = 1 - p_{k_1}^{(3)} \sum_{k_2=1}^{M} \rho_{k_1 k_2}^{2} (1 - p_{k_2}^{(2)}) +$$

$$p_{k_1}^{(3)} \sum_{k_2=1}^{M} \rho_{k_1,k_2} p_{k_2}^{(2)} \sum_{j_1=1}^{K} \rho_{j_1,k_2} \qquad (18)$$

The terms $I_{k_1}^{(3)}$ and $N_{k_1}^{(3)}$ in (17) represent the interference and noise terms introduced due to imperfect cancellation in using the soft output values from the second filter stage. The average SIR of the set-1 user at the output of the second stage, $SIR_{k_1}^{(2)}$ is then given by

$$SIR_{k_1}^{(2)} = \frac{2A_{k_1}^{2} X^2}{\sigma^2_{I_{k_1}^{(3)}} + \sigma^2_{N_{k_1}^{(3)}}} \qquad (19)$$

Likewise, the average SIR of the set-2 user at the output of the third stage, $SIR_{k_2}^{(3)}$ is then given by

$$SIR_{k_2}^{(3)} = \frac{2A_{k_2}^{2} X^2}{\sigma^2_{I_{k_2}^{(3)}} + \sigma^2_{N_{k_2}^{(3)}}} \qquad (20)$$

V. Simulation Results

This section presents the simulation results of the average SIR and Bit Error Rate (BER) performance of the proposed WLPIC scheme. The results are compared with those of CLPIC and matched filter detector. It is noted in all graphs that the weighted LPIC clearly outperforms both the MF detector as well as the conventional LPIC. The channel model used is a one sample spaced, two-ray, equal-gain Rayleigh fading and additive white Gaussian noise model. The data modulation is BPSK and the spreading factor N is 64. The number of set-1 users taken is 20.

In Fig.1, the BER performance comparison of scrambled scheme with weighted LPIC as a function of average SNR per bit with that of the MF detector as well as the

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conventional LPIC on flat Rayleigh fading channel and additive white Gaussian noise is observed. It is found that for 25% overloading the 3rd stage CLPIC and WLPIC approaches the single user detector. The Fig.2 at 41% overload supports an additional 8 users at a BER of greater than 10^{-3} for the 3rd stage WLPIC. However the performance of 2nd stage WLPIC and 3rd stage CLPIC deteriorates at a BER of 10^{-3}.

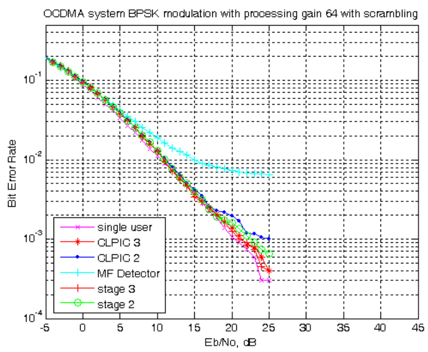

Figure 1. BER performance of scrambled system with 25% overloading and processing gain of 64.

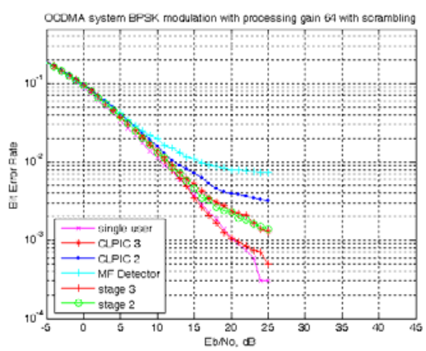

Figure 2. BER performance of scrambled system with 41% overloading and processing gain of 64.

In Fig. 3, the BER performance comparison of scrambled scheme with weighted LPIC with that of the MF detector as well as the conventional LPIC is observed at 50% overloading. The 3rd stage WLPIC supports an additional 10 users at a BER of 10^{-3}. Hence, complex scrambling increases the amount of overloading significantly in overloaded DS-CDMA systems. The performance degradation of 2nd stage WLPIC and 2nd and 3rd stage of CLPIC is large.

The BER increases at 64% overloading for both the WLPIC and CLPIC as shown in Fig. 4. It is observed in all graphs that the BER of 2nd stage CLPIC is large and the BER of the proposed 3rd stage WLPIC is less. Thus the proposed WLPIC scheme results in significantly better BER performance than both the matched filter detector as well as the CLPIC scheme. The 3rd stage of the WLPIC scheme is found to have high SIR.

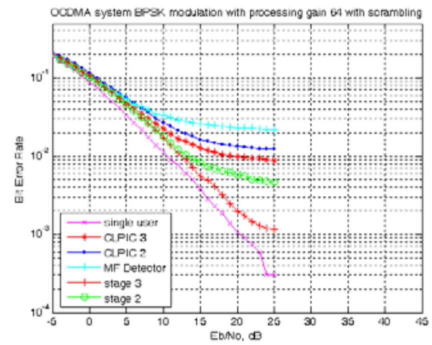

Figure 3. BER performance of scrambled system with 50% overloading and processing gain of 64.

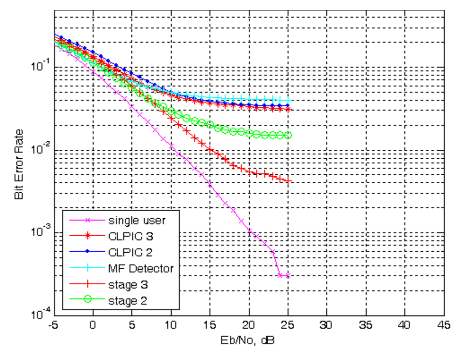

Figure 4. BER performance of scrambled system with 64% overloading and processing gain of 64.

VI. Conclusion

A new multiple access concept has been used in the direct-sequence code-division multiple access (DS/CDMA) concept to accommodate higher number of users than the spreading factor N. The BER performance was evaluated through MATLAB simulation. A two stage and three stage conventional and weighted parallel detection technique was used to cancel interference between the two sets of users. The signal to interference ratio of the two sets of users is also derived for the second stage and third stage. It is thus shown that the proposed technique provides 50% overloading at a BER of 10^{-3} supporting an additional 10 users.

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